Chemical Oceanographic Studies Along a Section From 32°S to Antarctica in the Southwestern Indian Ocean

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ABSTRACT

Water samples collected during the First Indian Expedition to Antarctica, were analysed for salinity, dissolved oxygen, pH. phosphate-phosphorus, nitrate-nitrogen, nitrite-nitrogen and silicate-silicon. These parameters were used to identify the regions of polar divergence, antarctic convergence and sub-tropical convergence. Within the limits of the available data, the existence of these three regions has been identified. Downward gliding of the nutrient-rich water along the continental slope of Antarctica was also recorded.

The atomic ratios of the change in A AOU: A Si: A N: A P were 285:58:19:1. A comparison of these with similar ratios from the northern Indian Ocean indicates an excess of 19% nitrate and 45% silicate in the southern Indian Ocean while the phosphate concentrations in both these seas were found to be quite similar. 'Reserved' fractions of phosphate and nitrate decreased significantly from the antarctic waters (south of the antarctic convergence) to the sub-antarctic waters found north of this region. This indicates that there is an increase in the intensity of oxidation process in these areas. Similar values of "reserved" silicate in both the regions indicate their origin from the oxidation and probably from other processes. Applying an empirical relationship between the silicate and AOU, it was observed that the lower ranges of silicate concentration were due to its consumption by siliceous algae, north of the polar divergence. Negative values between the observed and the calculated values suggest a transfer of oxygen from deeper layers to intermediate layers. Oxidative ratios do not indicate any difference in the rate of oxidation in the Indian Ocean region, north and south of the equator up to the zone of Antarctic convergence.

INTRODUCTION

Three major oceans— the Atlantic, Pacific and the Indian, have their common southern boundary in the southern ocean. The region between Australia, South America and Africa girdles the globe and allows free interocean circulation. This region promotes processes that equalize the characteristics of the three major oceans. Because of the importance of these processes and almost similar climatic conditions prevailing in the circumpolar zone, the sea is often given a separate name: the 'Antarctic Ocean', 'Antarctic Seas', or 'Southern Ocean(s)'. However, this ocean lacks a northern boundary in the classical sense, and hence its limit is arbitrarily fixed at a latitude marked by oceanographic processes such as a convergence or divergence.

For the purpose of the present study, we simply call the waters within this zone as the antarctic waters. Such a general term is used simply to identify the waters from the coasts of Antarctica northward up to the point of antarctic convergence. This region will also include the narrow belt of polar divergence near the antarctic coast. The water between the antarctic convergence and the subtropical convergence is the sub-antarctic waters. This term is best applied to the surface layers of this zone, since the intermediate, deep and bottom layers become more or less continuous across the antarctic convergence.

Almost all of the deep and bottom water masses of the three oceans originate in the antarctic waters. Perhaps, for this reason a number of reports of physical oceanographic, characteristics of the southern^ ocean are available. Similarly, because of the importance of "krill" and its phenomenal abundance south of the antarctic convergence, a number of reports on the biology of southern ocean have also appeared.

Clowes (1940) was the first to report on some aspects of the chemistry of the southern ocean from the data collected during the *'Discovery'* cruises. Several other reports (Jacobs 1966; Jacobs and Amos 1967)

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appeared on some hydrochemical aspects, mainly from the regions of Weddell Sea of the southern ocean. The first comprehensive report of the hydrochemistry of the Indian Ocean sector of the southern ocean is by Ivanenkov and Gubin (1960) based on the *'Ob'* cruises of 1956. Most of the analytical method, used by them, have since been refined and improved. The most recent record of the chemical observations in this region is by Jacobs and Georgi (1977) from the *'Conrad'* cruises of 1974. Thus, it is obvious, that there exists a big gap in our knowledge about a comprehensive picture on the hydrochemistry of the southern ocean.

Using the opportunity provided by the First Indian Expedition to Antarctica by the ship M.V. *'Polar Circle'*, several stations along a NE-SW transect from 69°S to 32°S in the southwestern Indian Ocean were worked. This paper gives a report on a few chemical parameters. Our findings are of a preliminary nature and we do not propose any definite and far-reaching conclusions from the data,

MATERIAL AND METHODS

Water samples were collected at 17 stations (Fig. 1) using 2 litre Niskin-type water samplers up to a depth of 2000 m. Due to technical difficulties, depths greater than 2000 m could not be generally sampled.

Parameters analysed on board were dissolved oxygen, pH, phosphate-phosphorus, nitrate-nitrogen, nitrite-nitrogen and silicate-silicon using the methods outlined by Grasshoff (1976).

RESULTS AND DISCUSSION

(a) Hydrography

The area covered by the transect includes the antarctic divergence, antarctic convergence and sub-tropical convergence.

The main flow of the circumpolar current around the antarctic continent is zonal, westward south of the antarctic divergence and eastward north of the divergence (Mosby 1934; Deacon, 1937). The surface and bottom water masses are of antarctic origin, in that their characteristics are acquired south of the antarctic convergence (Gordon, 1967). Their northward and downward components of motion are compensated by a southward and upward flowing deep water mass (Gordon, 1971). The results of this important meridional exchange indicate that heat and nutrients are brought to the surface of the antarctic waters from the lower latitudes and the oxygen content of the deeper water of the entire region is replenished. Such a process involves heat flux from the ocean to the atmosphere and a high rate of biological productivity in the photic zone which maintain proper conditions for the generation of living organisms in deeper waters and the establishment of low temperatures in the deep ocean.

To examine some of these characteristics, we plotted the iso-lines of several parameters e.g. salinity, phosphate-phosphorus, nitrate-nitrogen and silicate-silicon (Figs. 2-5). Nitrite-nitrogen was almost absent except in the surface layers where its concentration varied from 0.03 to 0.39 /xg-at/1. Higher values were seen south of the antarctic divergence. At the region of the sub-tropical convergence (stn. G17), the nitrite concentrations ranged from 0.53 - 0.71/xg-at/1 in the upper 100 m of the water column. Oxygen saturation ranged from 62% at about 4000 m depth to approximately 96% at 100 m. Super-saturation was observed at the surface. Occasional low values of 53-59% were recorded in the samples collected between 1000-1500 m depth range. We omitted these two parameters from our evaluation as it was felt that they may not have much influence in the identification of water masses.

Figure 2 gives the iso-halines. The upward movement of the high-saline water was seen south of 60°S. North of this latitude to about 45°, a downward movement of this water was observed. From 45°S to about 32°S, there was a clear indication of the water masses to move downward. These observations indicate the existence of the antarctic divergence, antarctic convergence and sub-tropical convergence in the three regions. Below 1000 m depth, the high salinity water indicates the flow of sub-antarctic waters. A study of the water masses along this section, using salinity (S),

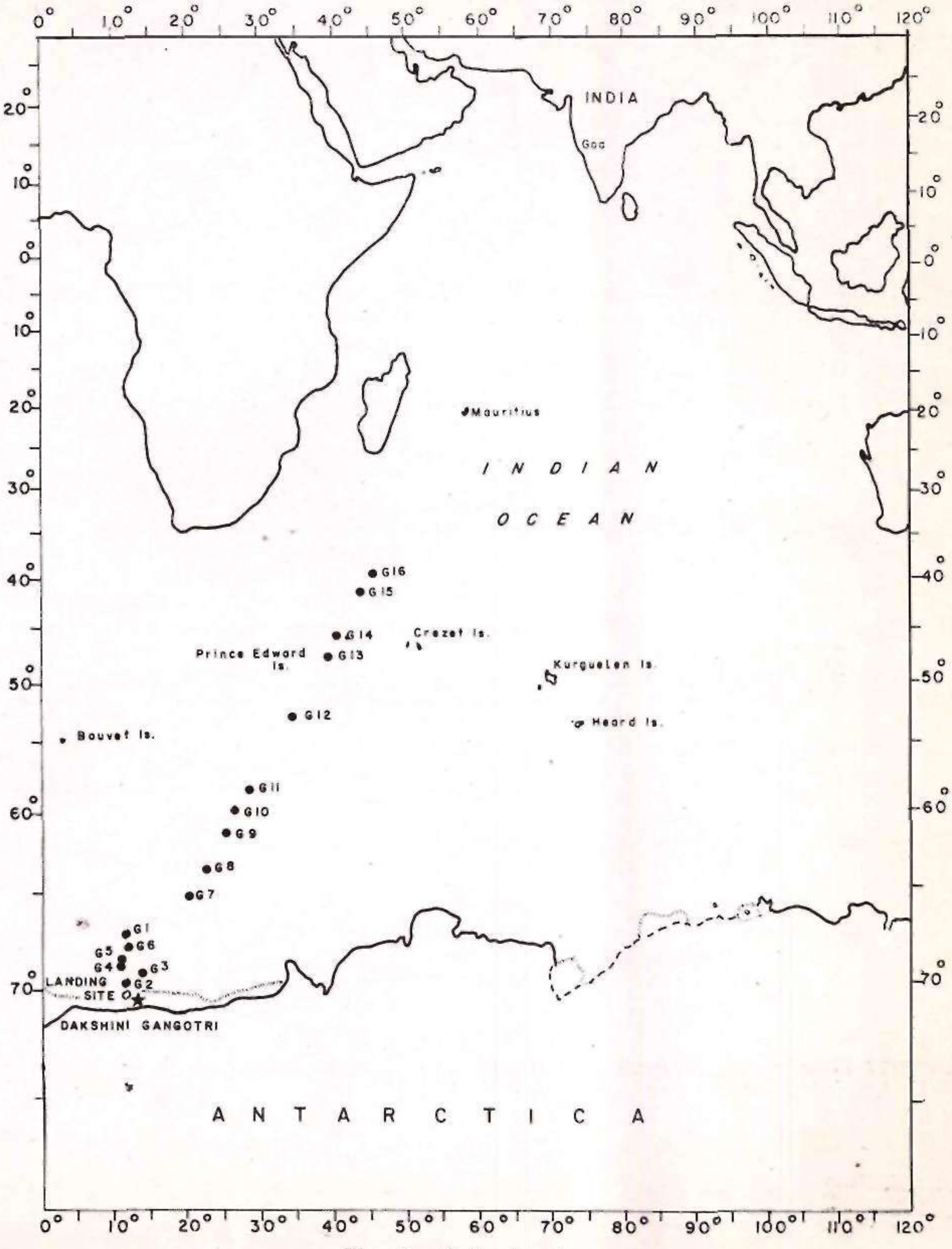

Fig. 1 : Station locations.

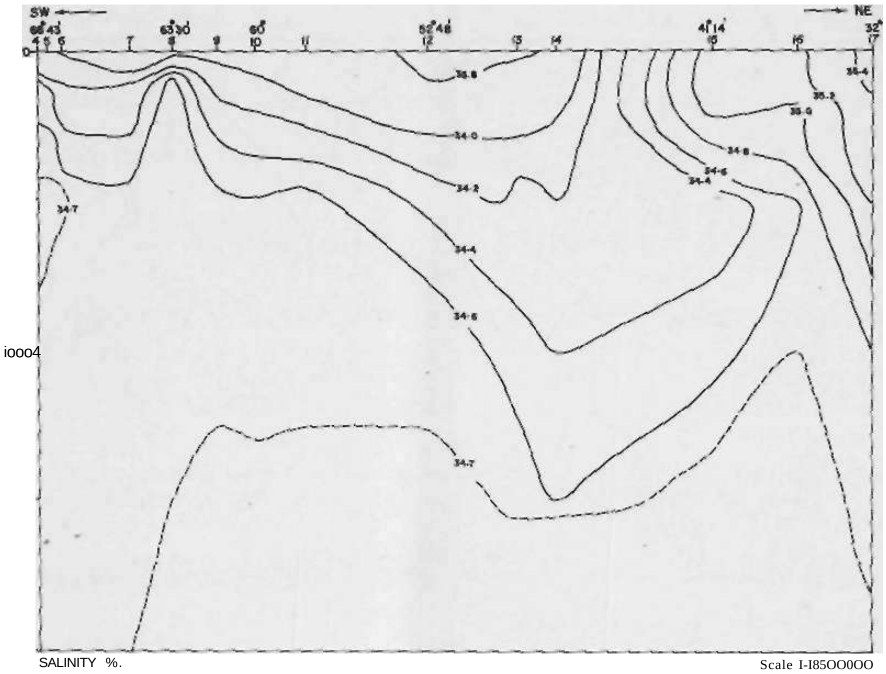

Fig. 2 : Isohalines along the sections.

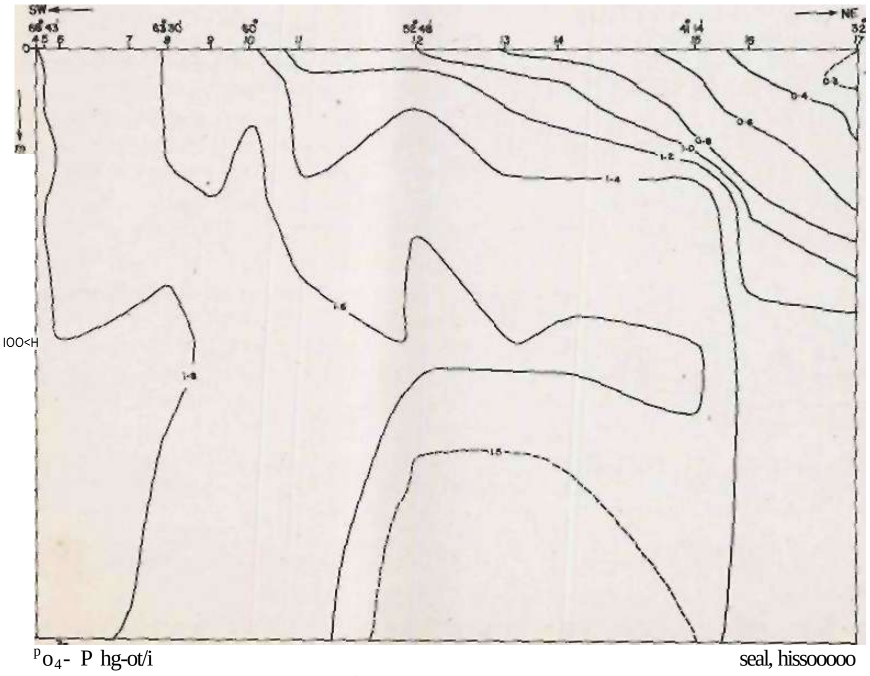

Fig. 3 : Isopleths of phosphate-phosphorus along the section.

potential temperature (0°C)and potential density (o-o)has been presented in this report by Rama Raju andSomayajulu.

Isopleths of phosphate-phosphorus (Fig. 3) give an interesting picture. From Fig. 3 it can be seen that there is a mixed layer varying in depth from 400 m at the stn. 8 to about 1000 m at stn. 4. This is probably the antarctic water formed by thermohaline convection during the winter. With the approach of summer conditions, the depth of mixed layer decreases northwards, away from the Antarctic continent and probably ends up where upwelling occurs in the region of polar divergence. North of 60°S, a clear sinking was observed all the way up to the station G17. This region probably covers the zones of antarctic convergence and sub-tropical convergence. Fig. 3 also indicates that the concentration of phosphate-phosphorus, at about 1000 m depth, decreases as we move away from the antarctic continent (from 1.8 to 1.6 /i.g-at/1). This is probably because of the presence of different water masses at this depth. Lower concentrations of phosphate-phosphorus has been recorded below the 1400 m depth in the antarctic convergence. This is probably the water of sub-antarctic origin which flows southward.

The isopleths of nitrate-nitrogen (Fig. 4) and silicate-silicon (Fig. 5) give almost a similar picture as that of the phosphate-phosphorus. There are trends of upward movement of water south of the divergence and downward movement in the regions of the convergence and also north of it. Decreasing concentrations Df phosphate-phosphorus have been noticed at the intermediate depths as we move away from the shores 3f the antarctic continent. However, in some of these situations, (Figs. 4 & 5), there appears to be the absence of the sub-antarctic water. Presumably the regeneration intensities of nitrate-nitrogen and silicate-silicon also differ. Nitrate-nitrogen undergoes processes of oxidation-reduction in the water :olumn while silicate-silicon gets added by sources other than nutrient regeneration. High concentrations >f these two nutrients at depths of about 1000 m at the southernmost stations probably, indicate *i* downward gliding of nutrient-rich water as we move away from the antarctic continent.

From the Figures 2-5 we can infer that in the area studied the polar divergence occurs between 60° and 63°S. The antarctic convergence is present in the region slightly south of 52°S, as indicated by the lines of downward movement. The antarctic convergence is a very prominent but arbitrary line of demarcation varying in its boundary from 48°S to 52°S in the vicinity of the antarctic continent (Gordon, 1967). Similarly we can also locate the boundary of the sub-tropical convergence in this region south of U°S.

!b) Nutrient Relationships

The inter-relationships between the 'Apparent Oxygen Utilization' (AOU) and the nutrients were :alculated by applying the linear least-square regression. The results (by atoms) obtained are as follows:

A AOU: A P = 285:1 (1)
A AOU: A N = 15:1 (2)
A N: A P = 19:1 (3)
A Si: A P = 58:1 (4)

Therefore, the consolidated atomic ratios of change in water becomes:

A AOU : A Si : A N : A P = 285 : 58 : 19 : 1 (5)

The relationships obtained for the northern Indian Ocean (Sen Gupta *et al,* 1976) were:

A AOU : A Si : A N : A P = 280 : 40 : 16 : 1 (6)

A comparison of the equations (5) and (6) indicates a significant difference between the ratios of silicate and nitrate in the southern Indian Ocean. This is, evidently, due to the presence of an excess of silicate and nitrate. In fact, silicate concentration in the Indian Ocean has been previously stated to be the

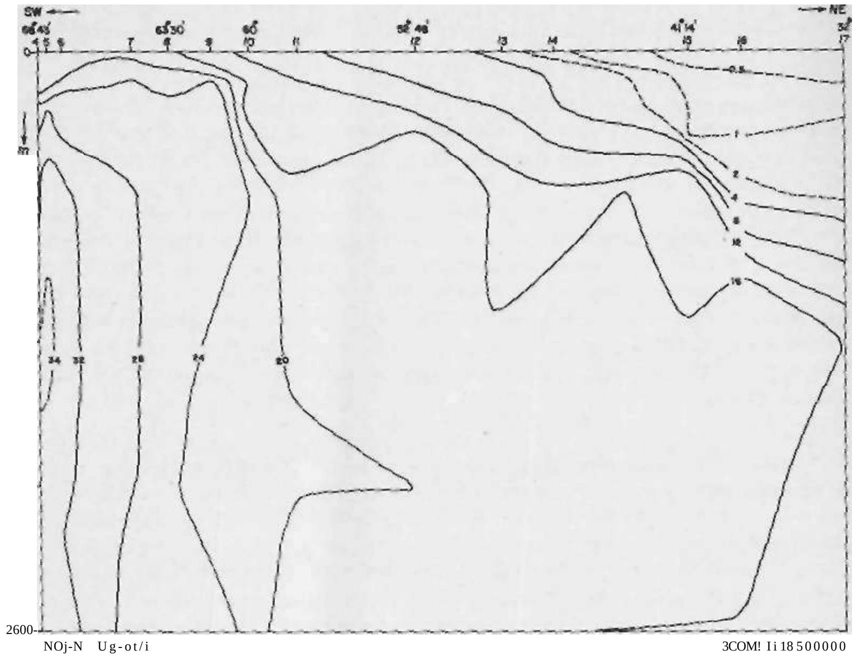

Fig. 4 : Isopleths of nitrate-nitrogen along the section.

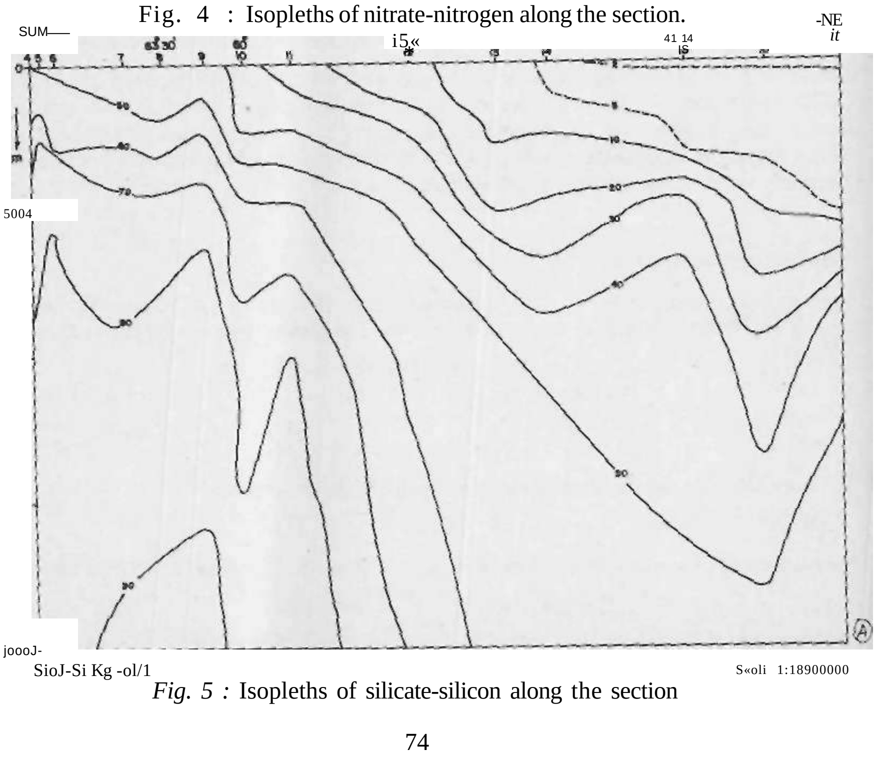

Fig. 5 : Isopleths of silicate-silicon along the section

highest in all the oceans of the world (Sen Gupta *et al,* 1976). Calculations based on the relationship between A N: A P and A Si: A P in the equations (5) and (6) indicate 19% excess of nitrate and 45% excess of silicate in the waters of the southern Indian Ocean as compared to those of the northern Indian Ocean. However, no excess of phosphate was observed in the southern Indian Ocean as the difference between A AOU: A P in both the regions can be considered to be within the limits of the statistical and analytical errors.

Higher concentrations of nutrients are to be expected in the waters south of the antarctic convergence, largely because of the presence of polar divergence and the melting of the ice. We, therefore, divided our area of study as south of 52°S and north of it upto 32°S. Concentrations of phosphate-phosphorus, nitrate-nitrogen and silicate-silicon were separated in their 'oxidative' and "reserved' fractions by applying the ratios indicated in the equation (5). The averages of all the values at all the depths and the stations are presented in Table 1.

TABLE 1

A verage values of nutrient fractions (in fig-at/l) at all the stations from surface to a maximum depth of 2000 m.

Fraction	All values	South of 52°S	52°S—32°S
P	1.52	1.72	1.14
Pox	0.75	0.83	0.61
Pr	0.77	0.89	0.53
N	19.4	24.4	10.2
Nox	14.2	15.6	11.7
N_r	5.2	8.8	-1.5
Si	58.6	75.2	27.9
Siox	5.4	9.6	3.0
Sir	53.2	65.6	24.9

From Table 1 the 'reserved' fraction of phosphate, can be worked put. The phosphate fraction gets reduced from 52%, of its total concentration in the region south of 52°S, to 47% towards north of this latitude. The nitrate fraction shows a remarkable decrease. Along south of 52°S, N_r was 36% of its total concentration, while towards north of the latitude N_r becomes negative. This indicates its consumption and the intensity of its oxidation in the water column. At almost all the stations in the zone of sub-tropical convergence, nitrate was absent in the topmost 100 metres layer. Oxygen concentrations were found to be low at the mid-depth. This indicates the intensity in the process of oxidation of organic matter. The inclusion of all these values of nitrate in the calculation has resulted in the negative N_r values given in Table 1.

The ' Reserved' fractions of silicate-silicon were found to be almost similar in both the regions (87% of the total concentration along south of 52°S and 89% north of it). Such a similarity would indicate that silicate is added to the water by processes other than oxidation of organic matter. In absolute values, Siox was found to be high in the colder waters because of the presence of large quantities of siliceous algae.

In an earlier work, Sen Gupta *et al* (1976) deduced the following relation between silicate and AOU:

$$AOU = 32 + Si^2/(0.12065 + 0.01025\ Si + 0.00197\ Si^2) \qquad (7)$$

This relation was obtained taking into account, the values of both the variables from the northern Indian Ocean. Using the equation (7) and the values obtained from the southern Indian Ocean, it is possible to determine the qualitative similarities or differences in the water characteristics of the northern and southern parts of the Indian Ocean. Thus the silicate values were pooled and averaged first in each 5 p.g-at/1 intervals upto a concentration of 10 Mg-at/1 and then into each 10 /xg-at/1 intervals up to the maximum observed values. The corresponding values of AOU were also pooled and averaged in a similar fashion.

The results obtained, including the differences between the observed and calculated values of AOU and the corresponding values of'reserved' fractions of silicate (calculations based on equation 5) are presented in Table 2 for the entire range of concentrations.

TABLE 2

Observed and Calculated Values of Silicate and AOU and 'Reserved' Silicate in Different Ranges of Silicate (all values in ^g-atll)

Range	Si	AOUobs	AOU_{calc}	AOU_{obs} - AOU_{calc}	Si_r (1)
0— 5	3.6	70	103	— 33	—10.4
5— 10	7.4	153	212	— 59	—23.2
10— 20	19.3(2)	185(2)	386	—201	— 17.7
20— 30	24.1	135	416	—281	— 2.9
30— 40	33.1	217	450	—223	— 10.3
40— 50	47.9	224	479	—255	3.1
50— 60	53.5	242	486	—244	5.1
60— 70	64.7	261	495	—234	12.6
70— 80	76.9	253	503	—250	26.3
80— 90	86.4	277	507	—230	31.0
90—100	91.8	291	509	—218	33.6

(1) A AOU: A Si = 5:1 by atoms
(2) From one value only

From Table 2 significant differences between the southern and the northern Indian Ocean can be obtained in the relationship between silicate and AOU. Low values of observed AOU and the negative values between the observed and the calculated values of AOU indicate a lower intensity of oxidation of organic matter at depths in the southern Indian Ocean as compared to northern Indian Ocean. The difference between the oxidative ratios in the equations (5) and (6) would indicate almost normal rates of oxidation of the organic matter, as is found at depths of the other oceans. Probable explanation for this could be the replenishment of the consumed oxygen from deeper waters. Also, in the northern Indian Ocean we have observed some silicate value at zero AOU. In the southern Indian Ocean no zero values of AOU were recorded during the present study.

'Reserved' fractions of silicate also indicate an interesting feature. Negative values of Sir in the concentration range 0-40 /xg-at/1 silicate-silicon were from the stations north of 60°S latitude i.e. far north of the region of polar divergence. All these low values were from the upper 100 - 50 metres of water. This probably indicates the consumption of silicate by siliceous algae without its being concurrently replenished by external sources.

The conclusions drawn in this report are of a preliminary nature as the data were obtained from 17 stations only. These were somewhat widely spaced and were worked only upto 2000 m depth and along a single transect. Many more observations at a network of stations covering a large area and the entire depth of water are needed to substantiate or modify the conclusions drawn above.

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